The Institute for Systems Research

Attacks and Defenses Utilizing Cross-Layer Interactions in MANET

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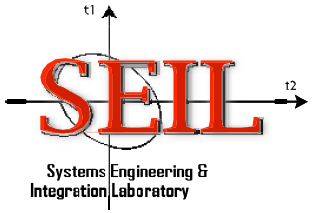
Motivation

- Possibility of Denial of Service (DoS) attacks in the MAC layer
- **MAC and routing layers interact**
- **Current protocols offer insufficient cross-layer interaction**
- Possible to cause an attack by **manipulating traffic in the MAC layer** and propagate attack to the routing layer
- **Need for additional interaction between MAC and routing:**
  - MAC needs to pass information to routing in case of congestion
  - Routing decides on new routes that are not affected by congestion;
  - IDS makes sure the new routes don't contain malicious nodes
- **Goal:** ***Detect the intrusion, minimizing detection time t_D and the number of false alarms, while maximizing the probability of detection P_D***

MAC Layer Issues

- Issues:
  - How to differentiate between an attack and congestion in wireless networks?
  - Randomness of Contention Window (CW) brings additional uncertainty in detection process
  - How long a node can stay malicious without being detected? What does it do in case of collision?
  - Is it realistic to assume the existence of stealthy attacks?
  - What is the number of nodes needed for attack detection, in particular partition detection?
  - Which parameters MAC and routing need to measure and exchange for efficient cross-layer Intrusion Detection Scheme?

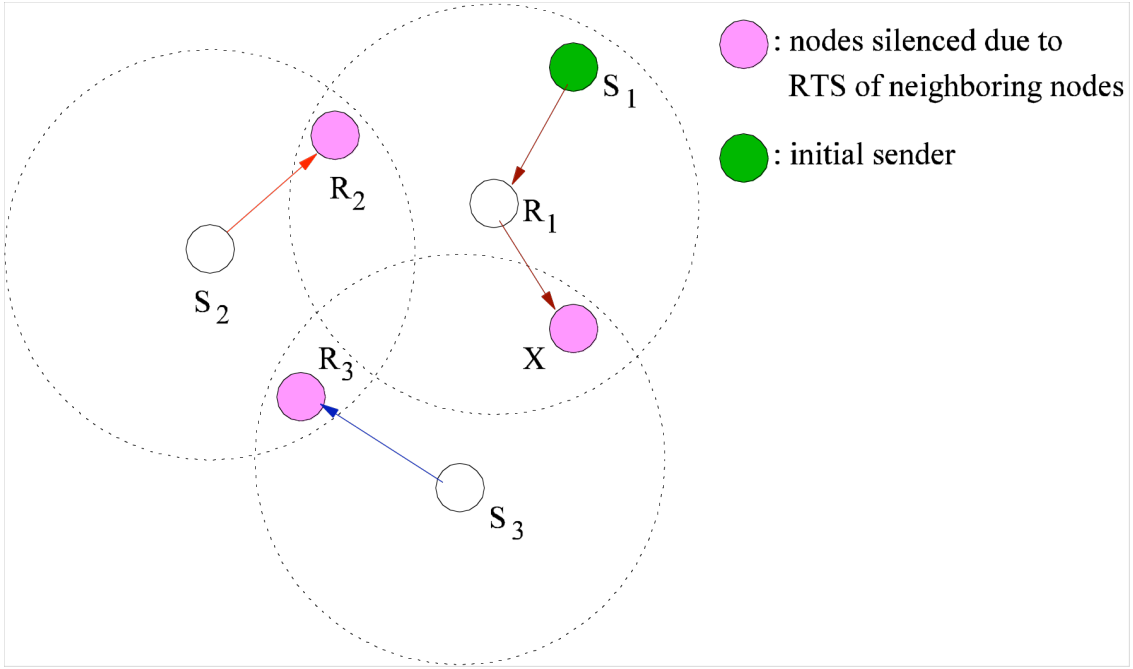


Routing issues

- Routing does influence the performance of MAC
- Routing chooses routes independently of MAC
- MAC only forwards the packet to the given node→may lead to failures
- Due to congestion and interference, MAC may not be able to deliver the packet
- Routing uses alternate route which is in vicinity of existing one →most likely unsuccessfully!
- Solution: let MAC and routing interact with each other and with the IDS
- IDS: has past behavior patterns and information from both MAC and routing;
    - Delivers final decision
    - Communicates with routing and MAC

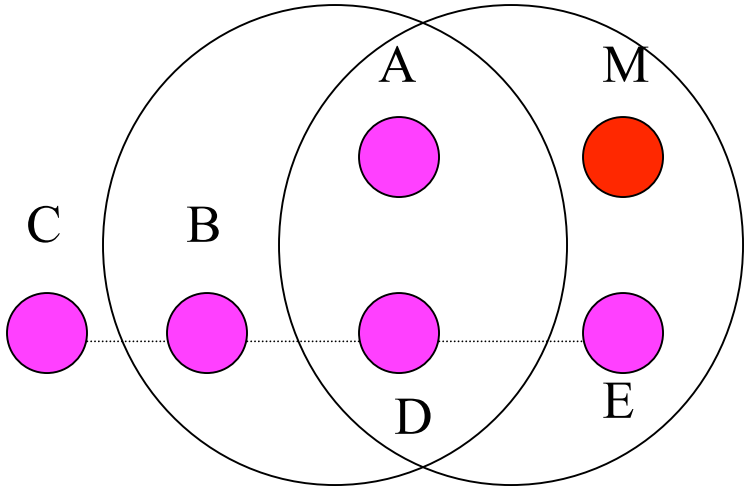
MAC issues

- Even without attacks MAC suffers from several problems:
  - RTS/CTS propagation
  - Unfairness due to exponential backoff
  - Path interference – can lead to chain reaction _*if attacked this way, not likely to find the attacker!*
- Solution:
  - Avoid *interfering paths*
- How?
  - Conflict graphs



Possible Attacks

Attack 1



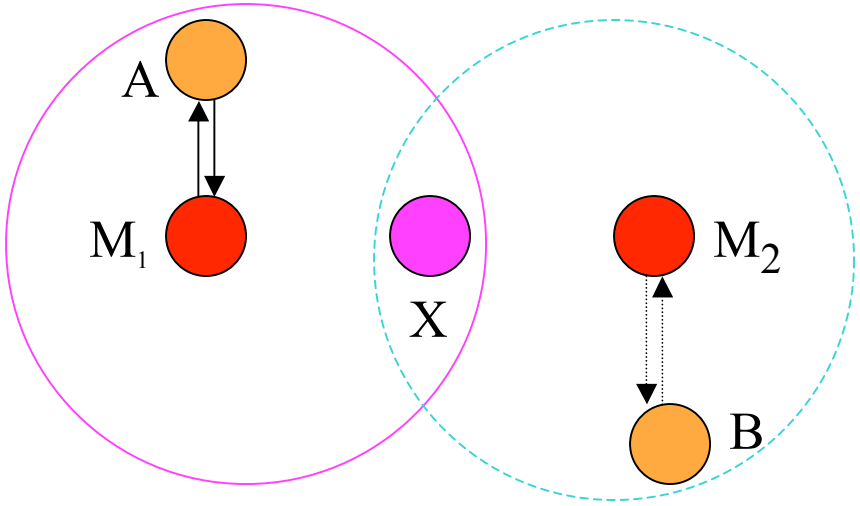
M "blocks" D from communicating

Attack 2

Two colluding attackers M_1 and M_2

First transmission M1 ⇨ A

X has to defer

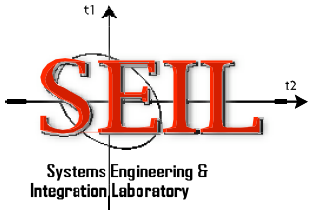


Second transmission M2 ⇨ B

X has to defer

M_1, M_2 synchronize

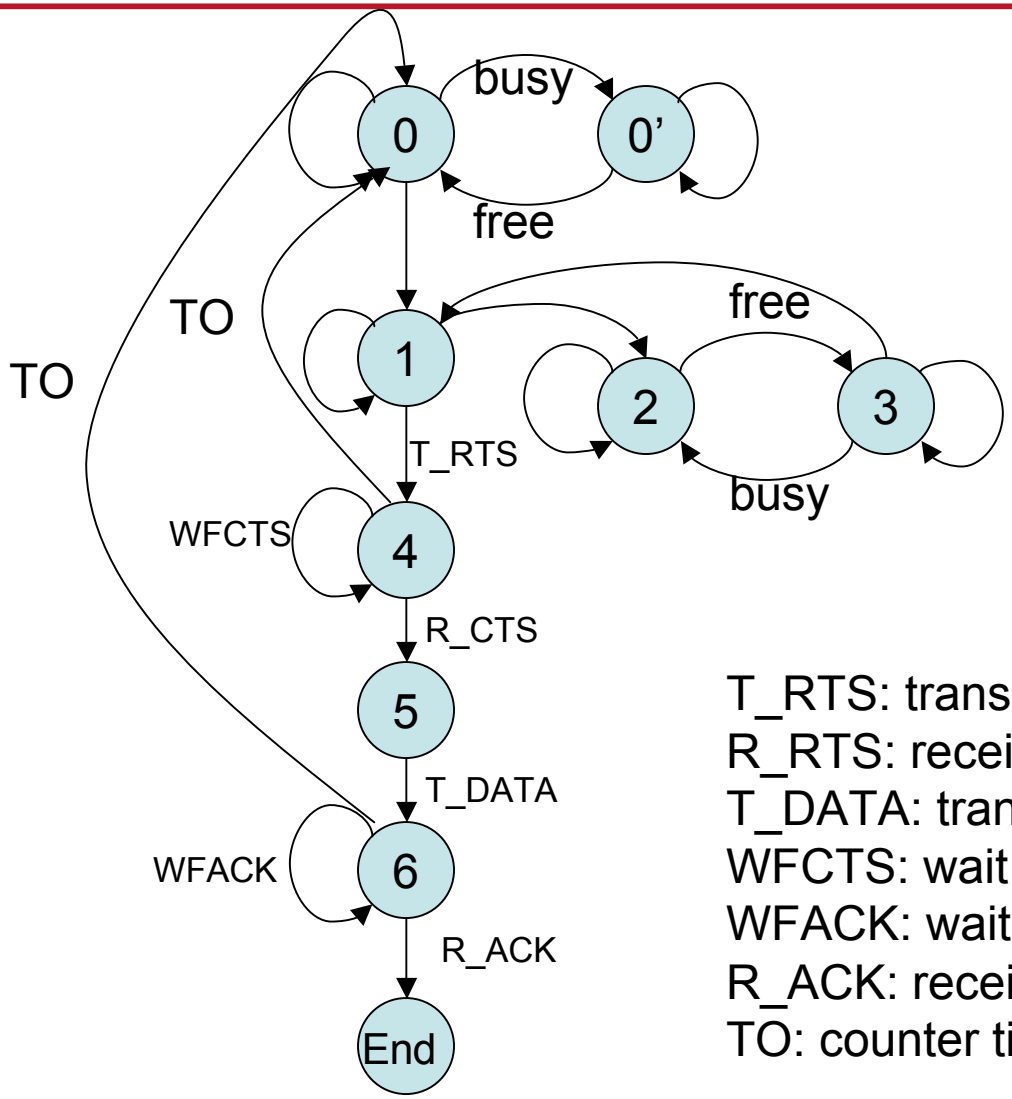
D is "blocked" from communicating



Node classification

- **Normal**
  - Obeys the rules of MAC layer protocols when both sending and receiving packets.
  - Will not behave selfishly and will reply to RTS requests from other nodes
  - Will update their CW, NAV etc. according to the rules of the protocol
- **Misbehaving**
  - ***Goal:*** gain priority in the network or disrupt already existing routes.
  - Usually change the value of **CW, NAV value, Duration/ID** field in the packet, etc.
- **Malicious**
  - All communication done following the MAC layer protocol
  - Will employ legitimate communications which result in DoS in one or multiple nodes and attack propagation through the network.
- **Issues:**
  - best strategy for detection of misbehaving nodes
  - How long a malicious node can stay malicious? Will it eventually collide with normal node?
  - What is the best strategy to stay undetected?
  - What about colluding nodes?

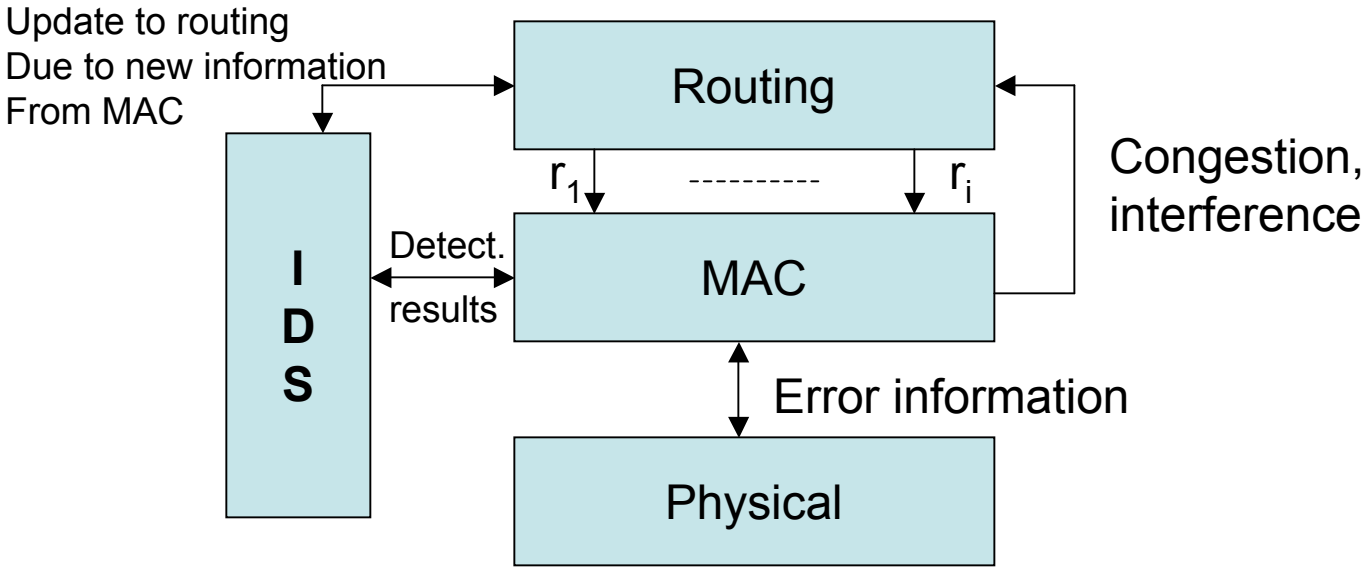
Formal Model



- MAC protocols easier to model than routing
- Represent MAC protocols in the form of EFSMs
- Need to impose **time constraints**
- In combination with logic useful as addition to IDS

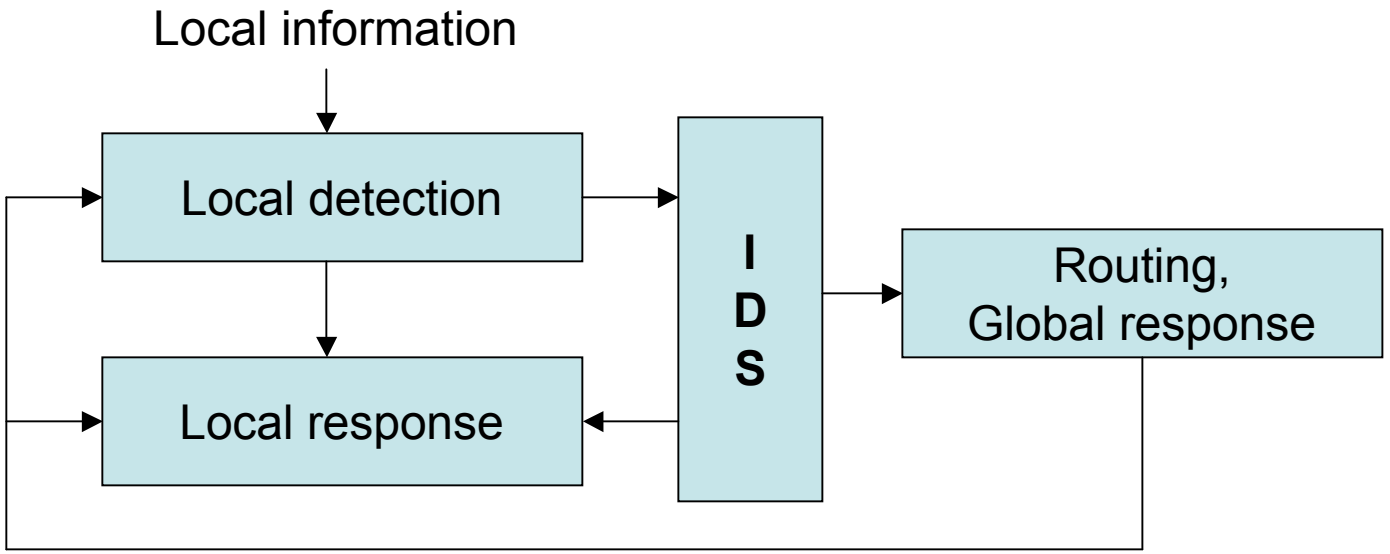
T_RTS: transmit RTS
R_RTS: receive RTS
T_DATA: transmit data
WFCTS: wait for CTS
WFACK: wait for acknowledgement
R_ACK: receive ACK
TO: counter timed out

Cross-layer scheme



- Routing sends several choices to MAC
- MAC uses: local detection, interference information, information from the physical layer,…
- MAC delivers the result back to routing _ subset of original routes
- Consults IDS if necessary->global detection

Detection scheme in MAC



- Input: local information
- Local detection: use Neyman-Pearson rule to detect the attack
- If not able to decide forward to IDS and let it decide
- Issue local (global) response and exchange the information with routing

Local Detection

P(*Receiver* = *busy*|*Sender* =*busy*) = 1

P(*Receiver* = *busy*|*Sender* = *idle*) = *p*

Hypothesis testing:

$$H_0 = \text{Sender is normal}$$

$$H_1 = \text{Sender is malicious}$$

Log-likelihood defined as:

$$L = \frac{P_{H_1}}{P_{H_0}} \underset{H_0}{\overset{H_1}{\gtrless}} \eta$$

Local Detection

- Due to channel conditions the receiver may not count the backoff correctly

B_S : the actual backoff of sender

B_r : backoff observed at the receiver side

B_t : threshold for backoff

Two cases:

$$B_r \geq B_t : P_{H_0} = 1 \wedge P_{H_1} = 0$$

$$B_r < B_t : P_{H_0} = P(B_s > B_t \mid B_r < B_t) = P(\text{making more than } B_t - B_r \text{ errors})$$

$$P_{H_1} = P(B_s < B_t \mid B_r < B_t) = P(\text{making } [0, B_t - B_r) \text{ errors})$$

Local Detection

- For $B_r < B_t$ log-likelihood ratio becomes:

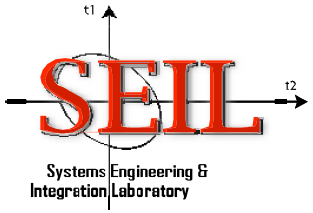
$$p^{B_r} \begin{matrix} H_1 \\ > \\ < \\ H_0 \end{matrix} \eta', \eta' = f(\eta, B_t, \text{assigned backoff})$$

- Decision rule:

$$H_1 : B_r < \eta'$$

$$H_0 : B_r > \eta'$$

$$H_1 \text{ with probability } \gamma : B_r = \eta'$$



Tradeoffs

- If B_r is increased, the number of errors is decreased (probability of correct, fastest detection increases).
- Log-likelihood ratio decreases with B_r increasing.
- When B_r increases the probability of classifying the node as normal increases.
- But the probability of false alarm increases
- Concerned about the probability of false alarm
- When backoff not fixed even normal nodes can transmit after a small number of idle slots.
- When backoff fixed, concerned about colluding nodes and malicious nodes listening to my transmission

Distributed detection

- Helps in decreasing number of false alarms and missing attacks
- *NP rule for distributed detection:*
  - *For a predetermined probability of false alarm,* P_F=_, *find optimum local and global decision rules* $\Gamma = (\gamma_0, \gamma_1, ..., \gamma_N)$ *that minimize the global probability of miss*

- Vector of local observations: $B_o = \{b_{o_1}, ..., b_{o_N}\}$
- Each node makes decisions based on local observations and sends its log-likelihood ratio to IDS
- Local decision vector: $u = \{u_1, ..., u_N\}$
- Global decision vector: $u_0 = \gamma_0(u), u_0 = \{0,1\}$

Distributed Detection

- Optimal test given by:

$$\Lambda(u) = \frac{P(u \mid H_1)}{P(u \mid H_0)} = \begin{cases} > \lambda_0, \text{ decide } H_1 \\ = \text{decide } H_1 \text{ with prob. } \gamma \\ < \lambda_0, \text{ decide } H_0 \end{cases}$$

  - Special case: P_D of all nodes are identical and P_F of all nodes are identical
  - The optimal decision rule becomes: $k \underset{H_0}{\overset{H_1}{\gtrless}} \eta'$

  k: number of nodes choosing H_1

$$\eta' = f(P_D, P_F, N, \eta)$$

Attack Detection

- For detection of more sophisticated attacks we formulate ***theorems*** (series of rules a fault-free MAC protocol cannot violate)
  - e.g. cannot violate exponentially growing contention window w.r. to next successful transmission time
- For **attack detection** Automatic Model Checking is executed with input of the relevant rule (theorem) parameters from the nodes under examination
- Non-allowed behaviors of system denoted as σ_i
- **Safety behavior**: σ
- σ is satisfied when $\neg\sigma_1 \wedge \neg\sigma_2 \wedge \ldots \wedge \neg\sigma_n$ are satisfied
- If there is σ_i s.t. the safe behavior is violated, the **model checker goes backwards and saves the time history** together with values of related variables
- **This scheme can be used for *automatic attack/fault generation***

Attack Detection

- The *vulnerable period* of IEEE 802.11 MAC is in RTS/CTS exchange
- We formulate the following theorem:
  - *Two processes cannot be in their critical section at the same time:*

$$AG(\neg(P_i.s = c \wedge P_j.s = c))$$

  - *A process that wants to enter its critical section is eventually able to do so:*

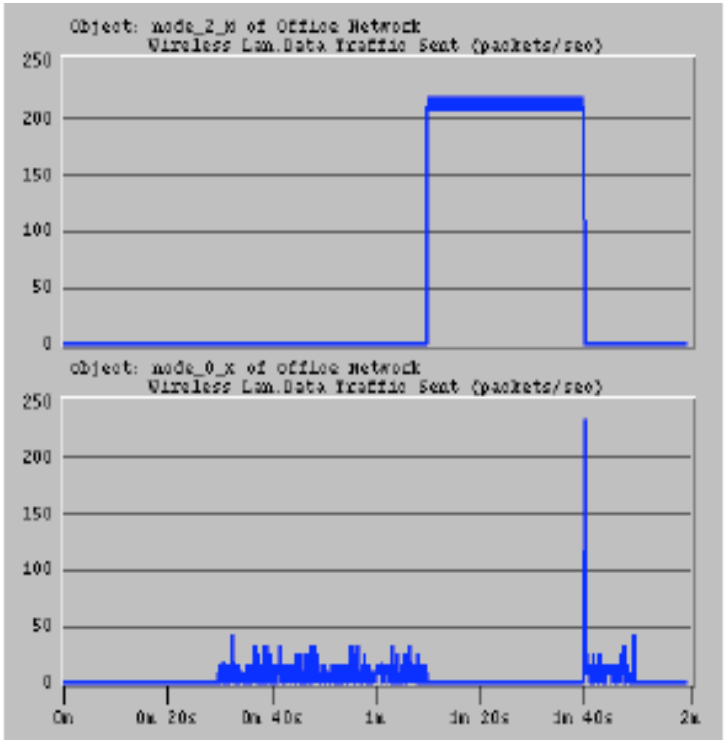
$$AG(P_i.s = A \Rightarrow AF(P_i.s = c))$$

- First rule helpful in case when other nodes assign backoff to sender!

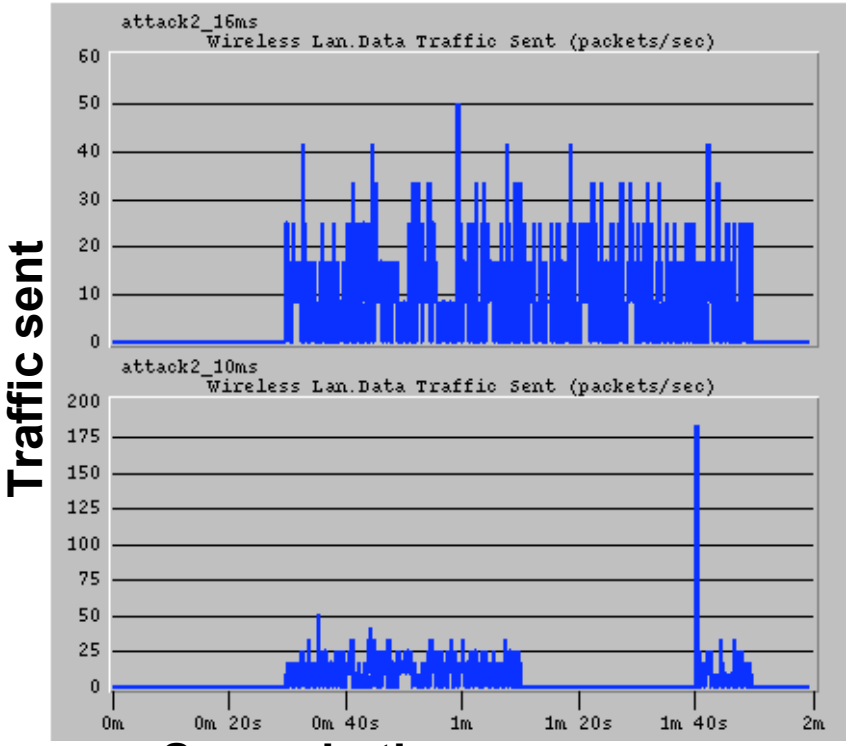
Results

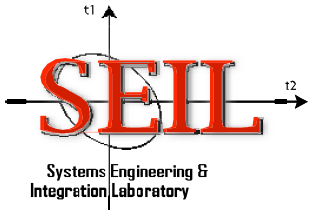
Attacks propagate from MAC to routing disabling key nodes:

Attack 1 results:



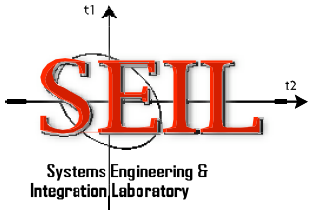
Attack 2 results:





Conclusions

- **Need to implement cooperation between MAC and routing** to be able to detect attacks more efficiently
- Other attacks apart from CW misuse exist: NAV, other kinds of backoff counter abuse, …
- **MAC can be modeled using Formal Models**
- Duration of malicious behavior depends on the traffic
- Stealthy attacks exist in short term, long-term existence depends on traffic and interference
- Conflict graphs good approach for solving problems of interference
- Need to simplify the problem since it's NP-complete!



Future Work

- Construct an Intrusion Detection System with ability to detect and classify known attacks using techniques presented and detect unknown attacks **using a database of attack features**
- How to detect anomalies in wireless networks?
- **Model other MAC protocols using EFSMs**
- Use the system for online attack generation that are passed to IDS and added to existing database of attacks
- Event ordering and correct timing have crucial roles in MAC protocols: necessary to **use ordered models of execution** with explicit timings
- Define the ordered model of execution with **multiple goals**
- Describe changes in state variables that lead to certain states

Future Work (cont.)

- Enable ***automatic attack generation*** **using EFSM models of MAC layer**
- **Challenges:**
  - Range of attacks is much wider in wireless than in wired networks;
  - How to distinguish between an attack and high volume of traffic?
  - **Which parameters to exchange between layers** to achieve efficient intrusion detection?
  - How to detect unknown attacks **without high false positive rate**?
  - Lack of data for testing; collaboration with industry and DoD Labs
- Potential approach - combination of model checking and theorem proving techniques.
- Plan to use a combination of analytical techniques from graph theory, dynamic games, distributed detection, temporal logic, hybrid automata